



Impacts of the Nuclear Symmetry Energy on Neutron Star Crusts[†] ^{*}

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Abstract Using the relativistic mean-field theory, we adopt two different methods, namely, the coexisting phase method and the self-consistent Thomas-Fermi approximation, to study the impacts of the nuclear symmetry energy on properties of neutron star crusts within a wide range of densities. It is found that the nuclear symmetry energy and its density slope play an important role in determining the pasta phases and the crust-core transition.

Key words symmetry energy—neutron star—methods: Thomas-Fermi

1. INTRODUCTION

It is generally believed that a neutron star mainly consists of a liquid core and crusts^[1]. Besides the spherical nucleus, the ones with exotic shapes, such as rod, slab, tube, and bubble, may also appear in the inner crust. That is to say, the so called pasta phases may appear there^[2,3]. It has been shown in Ref.^[4] that the inclusion of pasta phases could reduce the frequencies of shear modes and turn to be consistent with observations of quasi-periodic oscillations from soft gamma repeaters. The structure of the inner crust plays an important role in interpreting a number of astrophysical observations, especially the giant flares in soft gamma repeaters, neutron star oscillations, and glitches in the spin rate of pulsars^[5]. In the past decades, great efforts have been devoted to study the neutron star crust properties with various methods^[6,7].

The density dependence of symmetry energy is important for understanding many phenomena in both nuclear physics and astrophysics^[1]. The symmetry energy E_{sym} at saturation density is constrained by experiments to be 30 ± 4 MeV, however, its density

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slope L is still rather uncertain which may vary from about 20 to 115 MeV^[8]. Therefore, it is important and necessary to find a clear relation between slope L and crust properties. In this paper, we systematically study the effects of the symmetry energy E_{sym} and its slope L on the pasta phase properties and crust-core transition within the relativistic mean-field (RMF) theory by using two different methods, the coexisting phases (CP) method and Thomas-Fermi (TF) approximation.

2. MODEL AND METHODS

We adopt the Wigner-Seitz (WS) approximation to describe the inner crust matter, in which the charge neutrality and β equilibrium conditions are satisfied. The electrons are assumed to be uniform in the WS cell because the electron screening effect may be negligible at subnuclear density^[9]. We use the RMF theory to describe the nucleon interaction. The Lagrangian density is given by

$$\begin{aligned} \mathcal{L}_{\text{RMF}} = & \sum_{i=p,n} \bar{\psi}_i \left\{ i\gamma_\mu \partial^\mu - (M + g_\sigma \sigma) - \gamma_\mu \left[g_\omega \omega^\mu + \frac{g_\rho}{2} \tau_a \rho^{a\mu} + \frac{e}{2} (1 + \tau_3) A^\mu \right] \right\} \psi_i \\ & + \bar{\psi}_e [i\gamma_\mu \partial^\mu - m_e + e\gamma_\mu A^\mu] \psi_e \\ & + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 \\ & - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4} c_3 (\omega_\mu \omega^\mu)^2 \\ & - \frac{1}{4} R_{\mu\nu}^a R^{a\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu^a \rho^{a\mu} + \Lambda_v (g_\omega^2 \omega_\mu \omega^\mu) (g_\rho^2 \rho_\mu^a \rho^{a\mu}) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \end{aligned} \quad (1)$$

In order to check the model and method dependence of the results obtained, we adopt the parameter sets of Bao et al.^[10] in the CP method, while in the TF approximation, we employ the parameter sets of Bao et al.^[11]. These parameter sets were generated from TM1^[12] and IUFSU models^[13], which have the same isoscalar properties and fixed symmetry energy but have different symmetry energy slope L .

3. RESULTS AND DISCUSSION

We first present the phase diagram obtained in the CP method in Fig.1. It is found that a smaller L may get more complex pasta phase structure, while only the droplet phase may appear before the crust-core transition for a larger L . We can see that the crust-core transition density decreases with increasing L .

In Fig.2, the results obtained in the TF approximation are displayed. The L dependence of pasta phase structure and crust-core transition is similar to the results of CP method as shown in Fig.1. But unlike the CP case, the bubble phase may appear in the TF calculation for a small L . It is seen that there are quantitative differences between the CP and TF methods.

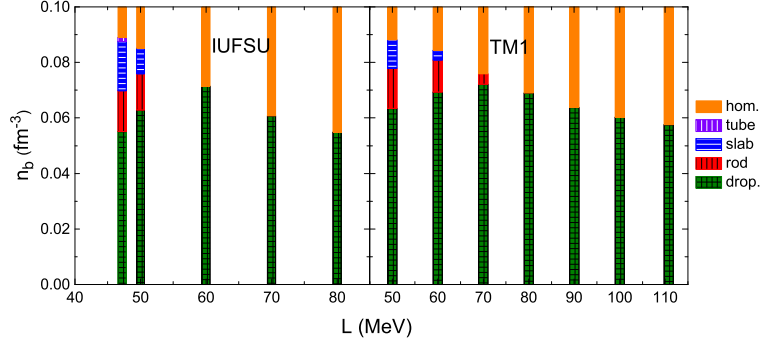


Fig. 1 Phase diagram obtained in the CP method. Different colors represent corresponding pasta and homogeneous phases as indicated in the legend.

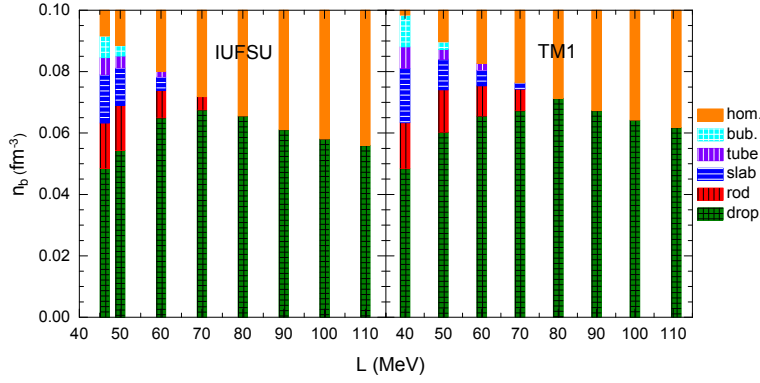


Fig. 2 Phase diagram obtained in the TF approximation. Different colors represent corresponding pasta and homogeneous phases as indicated in the legend.

In this work, we consider the crusts of cold neutron stars, so the calculation is performed at zero temperature. It is interesting to study pasta phases at finite temperature in the future.

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